FATIGUE LIFE ESTIMATION OF ITER CONDUITS AT 4 K

J. Feng

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

ITER superconducting magnets are designed to operate at 4 K under cyclic loading. The conduits of the magnets (e.g., central solenoid) are designed to support all the cyclic loads during operation. It is expected that fatigue fracture is the major failure mechanism for the conduits. In the present study, the fatigue life of the conduits for ITER and the model coil has been estimated by applying numerical integration of the Paris equation to a surface crack. The fatigue crack growth behavior of a 3D crack is analyzed. Discussion is given to three key factors of a 3D crack: crack type, crack aspect ratio, and the eccentricity of an embedded crack. It is found that the estimated fatigue life of the conduits for ITER or the model coil is acceptable based on the current ITER design criteria. In a thin plate, there is a linear-log relationship between the fatigue life and applied stress at given initial crack size. Either a surface or corner crack shows a shorter life than most embedded cracks. The fatigue life decreases as the crack eccentricity increases.

INTRODUCTION

ITER superconductor magnets are designed to operate at 4 K under EM cyclic loading. The conduit of the magnets (e.g., central solenoid) are designed to support all the cyclic loads during operation. The fatigue fracture of the conduits is expected to be a major failure mechanism.\(^1\)

Over last several decades, extensive studies have been published for the test results and life estimation of a part containing a 2D crack (e.g., a single-edge notched crack and central crack).\(^2\) However, it is found that most cracks in an engineering component are 3D cracks (e.g., a surface, corner or embedded crack). Such 3D cracks are more complicated in stress and strain distribution than 2D cracks. There is no simple and accurate solution to estimate the life of a 3D crack. A typical treatment is to apply the 2D crack test data to a 3D crack stress field.

In this paper, the fatigue life of ITER conduits is estimated by assuming an existing 3D crack to propagate until a critical size. The fatigue propagation behavior of a 3D crack in a thin plate is analyzed. The fatigue life is calculated by using two-point integration method for the conduits as well as tension link / interface shear bars of ITER model coils at 4 K. Finally, discussion is given for several key factors to affect the fatigue life.
FATIGUE LIFE ANALYSIS OF A CRACK IN A THIN PLATE

The fatigue crack growth rate under constant stress amplitude is expressed by the Paris equation, which is valid only for small-scale yielding at the crack tip (linear-elastic fracture mechanics),\(^2\)

\[
\frac{da}{dN} = c(\Delta K)^n, \tag{1}
\]

where stress intensity factor range \(\Delta K = K_{\text{max}} - K_{\text{min}}\), \(c\) and \(n\) are Paris parameters, \(a\) and \(N\) are the half crack length and fatigue cycle respectively.

Increasing the mean stress \((\sigma_{\text{max}} + \sigma_{\text{min}})/2\) for an applied stress range \((\sigma_{\text{max}} - \sigma_{\text{min}})\) generally shortens fatigue life. The effect of mean stress is often expressed by an effective stress intensity factor range:\(^3\)

\[
\Delta K_{\text{ef}} = K_{\text{max}}(1 - R)^m = \Delta K(1 - R)^{m-1}, \tag{2}
\]

where \(R\) is the stress ratio \((\sigma_{\text{min}} / \sigma_{\text{max}})\) and \(m\) is the Walker exponent.

Combining Eqs. 1 and 2 gives:

\[
\frac{da}{dN} = c(\Delta K)^n(1 - R)^{(m-1)n}, \tag{3}
\]

where \(\Delta K = Y\Delta\sigma\sqrt{\pi}a\), and \(Y\) is the crack geometry factor. Eq. 3 may be written as

\[
\frac{da}{dN} = c(K_{\text{max}})^n(1 - R)^{mn}, \tag{4}
\]

where \(K_{\text{max}} = Y\sigma_{\text{max}}\sqrt{\pi}a\).

Integration of Eqs. 3 or 4 gives the fatigue life (the number of cycles to failure):

\[
N_f = \sigma_{\text{max}}^{-n}(1 - R)^{-mn} \xi, \tag{5}
\]

where \(\xi = \frac{1}{c} \int_{a_i}^{a_f} \frac{da}{Y^n(\pi a)^{n/2}} \).

The expression for \(\xi\) can also be obtained in terms of crack depth \(b\), instead of the semi-crack length \(a\), based on the known crack aspect ratio of \(b/a\). Note that the \(Y\) expression must be modified accordingly:

\[
\xi = \frac{1}{c} \int_{b_i}^{b_f} \frac{db}{Y^n(\pi b)^{n/2}}, \tag{6}
\]

where \(b_i\) and \(b_f\) are initial and final crack depths respectively.

For a thin plate, e.g., the conduit wall, the upper integration limit \(b_f\) is the wall thickness. Therefore, \(\xi\) is independent of applied stress and only a function of the Paris parameters \((c, n)\), the initial crack size and conduit geometry. \(\xi\) can be obtained by a numerical integration using a finite difference method:

\[
\xi = \frac{1}{c} \sum \frac{\Delta b}{Y^n(\pi b_j)^{n/2}}. \tag{7}
\]

Taking logarithms of both sides of Eq. 5 gives